Wee Jasper–Lake Burrinjuck Fossil Fish Sites: Scientific Background to National Heritage Nomination

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The ~5 km thick Burrinjuck Devonian sedimentary sequence records environmental change from a volcanic terrain with deep lake deposits (oldest), through a tropical reef marine ecosystem, to river and lake deposits (youngest). Numerous fossil horizons document evolutionary change through the final stage of terrestrialization of the earth's biota. Exceptional exposures of Devonian tropical reefs in the Wee Jasper valley, with limestones washed completely clean by the waters of Lake Burrinjuck, have produced the world's oldest known coral reef fish assemblage. Including associated invertebrates, the faunal list stands at some 266 fossil genera.

Burrinjuck produced five key fossil fish specimens used in the 1940s in London to develop the acetic acid technique for extracting bone from calcareous rock (now standard in laboratories throughout the world). Recognizing the uniquely preserved early vertebrate braincase structures, the British Museum (Natural History) mounted two collecting expeditions to Burrinjuck (1955, 1963), when some 560 specimens were removed to London. Repatriation of type specimens is a future issue. The largest collection of Burrinjuck early vertebrate braincase material is housed at the Australian National University in Canberra; at least 70 fossil fish species represents biodiversity unequalled at any other Devonian fossil fish locality. Fossil site protection for the Burrinjuck area was the basis for a recent nomination for National Heritage listing. Long-term protection of natural history collections in the National Capital as part of Australia's scientific heritage is a related issue of concern.

INTRODUCTION

The Devonian Period (~418-360 million years ago), known as the 'Age of Fishes', was the geological period when the early jawed vertebrates underwent their first great evolutionary radiation. This included not only abundant and diverse fishes in all habitable aquatic environments, but also an evolutionary expansion of our ancestors (the first four-legged land animals) into an entirely new terrestrial environment, made habitable by the rise of land plants including the first forests during the Devonian Period. One of the NSW geological heritage sites (Taemas-Cavan) described by Percival (1985, pp. 30-33) represents the Devonian Period, and occupies the southeastern arm of Lake Burrinjuck, about 50 km NW of the National Capital in southeastern Australia (Fig. 1). In that area, Early Devonian marine limestones display spectacular folding, and richly fossiliferous shell beds such as are exposed at the 'Shearsby's Wallpaper' protected site.

Taemas-Cavan is the easternmost of two main areas of outcrop of Devonian limestones around Burrinjuck Dam (Fig. 1B). The western outcrop, surrounding the village of Wee Jasper in the valley of the Goodradigbee River, is separated by the Narrangullen anticline, where underlying older units (Mountain Creek Volcanics; Kirawin Formation; Sugarloaf Creek Formation) are exposed. Research on the geology and especially the vertebrate palaeontology of the Burrinjuck area has given it national and international significance. In March, 2010 the author lodged a nomination for part of the western outcrop of the Burrinjuck limestones to be included on the National Heritage List (areas labelled (I), Fig. 1C). Significant cave and karst structures documented by A. Spate form part of that nomination but are not dealt with further here (for details contact A. Spate, Optimum Karst Management). In this paper I summarise the geological and palaeontological significance of the Devonian sequence, with special
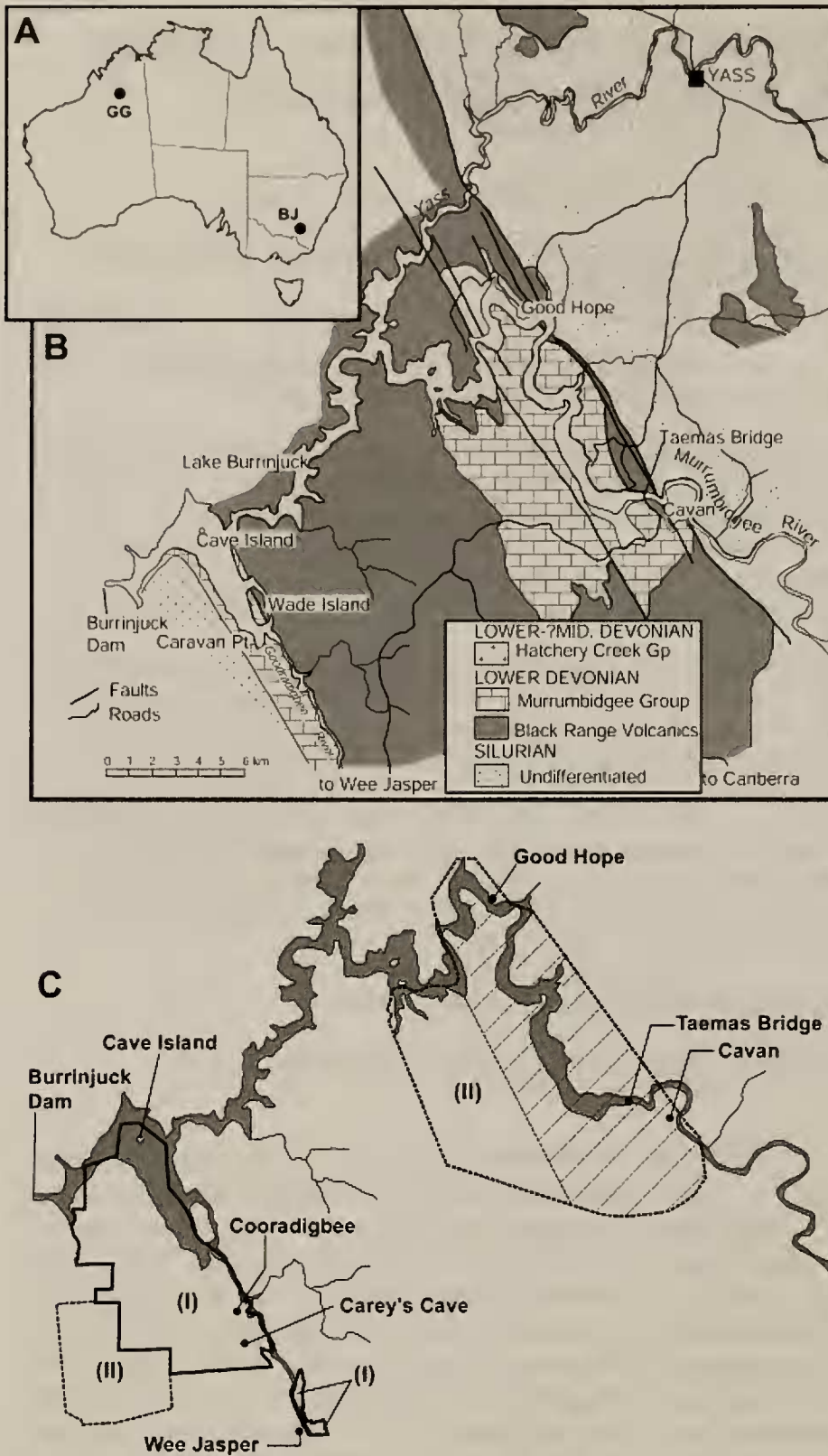
Figure 1. A. General localities for the two Australian limestone reef fossil fish assemblages from the Devonian Period (~418-360 million years ago): Gogo, WA (GG) and Burrinjuck, NSW (BJ). B. Geological map of the Burrinjuck area showing the two outcrops of Murrumbidgee Group limestones: Good Hope – Taemas - Cavan in the east, valley of the Goodradigbee River in the west. C. Lake Burrinjuck (shaded) on the Murrumbidgee River, with location of the area nominated for heritage listing in March 2010 (labelled (I), indicated by solid outline). Proposed future Stage II nomination (labelled (II)) indicated by dashed outline, including the NSW geological heritage area of Percival (1985, map 9) indicated by cross-hatching. Other localities mentioned in the text also labelled ('Cave Island = pre-dam 'Cave Flat').

reference to the remarkable fossil vertebrate remains that have been extracted from the Burrinjuck limestones. A brief summary of recent results of ongoing research is presented.

HISTORY OF SCIENTIFIC INVESTIGATION

The limestones of the Goodradigbee and Murrumbidgee valleys were doubtless well known to the indigenous population for many thousands of years, because of their interesting rock formations and caves. The limestone outcrops were first noted by Europeans as early as 1824 (by Hume and Hovell), and in 1836 fossil corals were collected from the area by the explorer Thomas Mitchell (Mitchell 1838). From 1848, the 'Father of Australian geology' Rev. W.B. Clarke made many collections in the area (Clarke 1860, 1878), which he sent overseas for expert determination (de Koninck 1877) to confirm the Devonian age for the limestones. Bennett (1860, p. 158) mentioned visits to the 'Gudarigby Caverns', apparently the limestone caves at Cave Flat near the junction of the Murrumbidgee and Goodradigbee rivers. Etheridge (1889) reported on a visit to these caves, where a spectacular *Thylacinus* skull was collected, and displayed for many years in the fossil gallery of the Australian Museum, Sydney (see Fig. 4A).

Etheridge recognized the exceptional fossil content of the limestones, which he described in the following terms (1889, p. 36): 'The Murrumbidgee limestone is ... crammed with fossils, especially corals. As a display of these beautiful organisms in natural section I have never seen its equal. Large faces of limestone ... may be seen, with the weathered

corals … standing out in relief and in section also. Many of these masses of coral, particularly those of *Stromatopora* and *Favosites*, are as much as 4 feet in diameter.'

A few years later Etheridge also visited the 'caves at Goodravale, Goodradigbee River' (now Carey's Cave, Wee Jasper valley, included in the heritage nominated area; see Fig. 1C), where cave deposits produced jaw remains of the marsupial lion *Thylacoleo* (Etheridge 1892). Etheridge (1906) then reported the first discovery of a Devonian lungfish from Burrinjuck, at that time the oldest known representative of the Dipnoi (see below). Harper (1909) conducted a geological mapping survey preliminary to the proposal to dam the Murrumbidgee River in the Burrinjuck area.

After construction of Burrinjuck Dam (1912-17) the area became more widely visited, and was a regular destination for geology student excursions from the University of Sydney. The subject matter of Professor T.W. Edgeworth David's first Australian publication (1882) was the geology and palaeontology of this area, and Dr Ida Browne did detailed stratigraphy and produced the first geological maps (Browne 1954, 1959). Her 1959 paper, including her widely used geological map of the Taemas area, was part of a publication to mark the centenary of the birth of Professor Edgeworth David. In recent decades Burrinjuck has been a focus for geology student excursions from many universities, and especially the ANU in Canberra, because of proximity and research interest. With more frequent droughts in recent years the rock exposures and fossil sites along the shores and on the bed of Lake Burrinjuck are now often accessible for extended periods.

BURRINJUCK DEVONIAN SEQUENCE

The Devonian Period lasted for some 60 million years. However, the exceptionally thick Burrinjuck Devonian sequence, comprising some 5 km of sedimentary strata overlying an equivalent or greater thickness of volcanics (Fig. 2), was mainly deposited during the early part of the Devonian Period (see below). A general observation is a strong cyclicity evident on a larger scale through some 3 km of stratigraphic thickness comprising the uppermost Hatchery Creek Group, and the Murrumbidgee Group limestones. In the limestones this is manifested as more recessive units comprising shale/limestone interbeds alternating with more massive limestones as constituent members of the Taemas Limestone (Browne 1959, Young 1969, Pedder et al. 1970).

In the Hatchery Creek Group fining-upward cycles occur throughout the succession, but with generally finer and less thick cycles higher in the sequence (Hunt and Young 2010). Google images to the east of Wee Jasper suggest a downward continuation of this cyclicity into the underlying Sugarloaf Creek Formation. The phenomenon could relate to orbital forcing causing regularity in climatic fluctuations (Hunt and Young, submitted). Elsewhere (e.g. Middle Devonian of Scotland, Late Devonian Munster Basin of southwest Ireland) smaller scale (36, 55 m) and larger scale (130 m) sedimentary cycles have been attributed to 100 Ka and 412 Ka Milankovitch Cycles respectively, with somewhat lesser thicknesses (8, 40 m sedimentary cycles) attributed to 21 Ka and 100 Ka Milankovitch Cycles in the largely lacustrine Orcadian Basin (Kelly 1992, Kelly and Sadler 1995, Marshall et al. 2007). This aspect of the Burrinjuck Devonian sequence has not been researched in any detail.

The last comprehensive accounts of the Devonian stratigraphy were by Owen and Wyborn (1979) for the Brindabella 1:100 000 geological map, and by Cramsie et al. (1978) for the northern part of the outcrop on the Yass 1:100 000 geological map. The following stratigraphic summary (oldest to youngest) relies heavily on Owen and Wyborn's (1979) explanatory notes (microfiche portion, now converted to pdf).

Mountain Creek Volcanics

The name was first published by Joplin et al. (1953). Some authors grouped this unit with the overlying Kirawin and Sugarloaf Creek Formations as the 'Black Range Group', but Owen and Wyborn (1979) considered these three units too dissimilar to be grouped together. The upper part of the Mountain Creek Volcanics in the Cavan area comprises rhyolites and tuffs deposited in a terrestrial environment. Estimated total thickness farther south is 5000-8000 m (Owen and Wyborn 1979, p. M190). The Mountain Creek Volcanics are considered to be entirely Devonian (probably mostly Lochkovian) in age, on the assumption that rhyolites at Mount Bowning on the Yass 1:100 000 sheet are equivalent (Link 1970). These rhyolites overlie lowermost Devonian strata containing the early Lochkovian conodont *Icriodus woschmidti* (Link and Druce 1972; see Pogson 2009 for updated comment on the conodonts).

Kirawin Formation

This black shale/mudstone deposit forms a poorly exposed outcrop 0.5 to 4 km wide, in an arcuate 35 km belt across the Narrangullen anticline. The outcrop thins
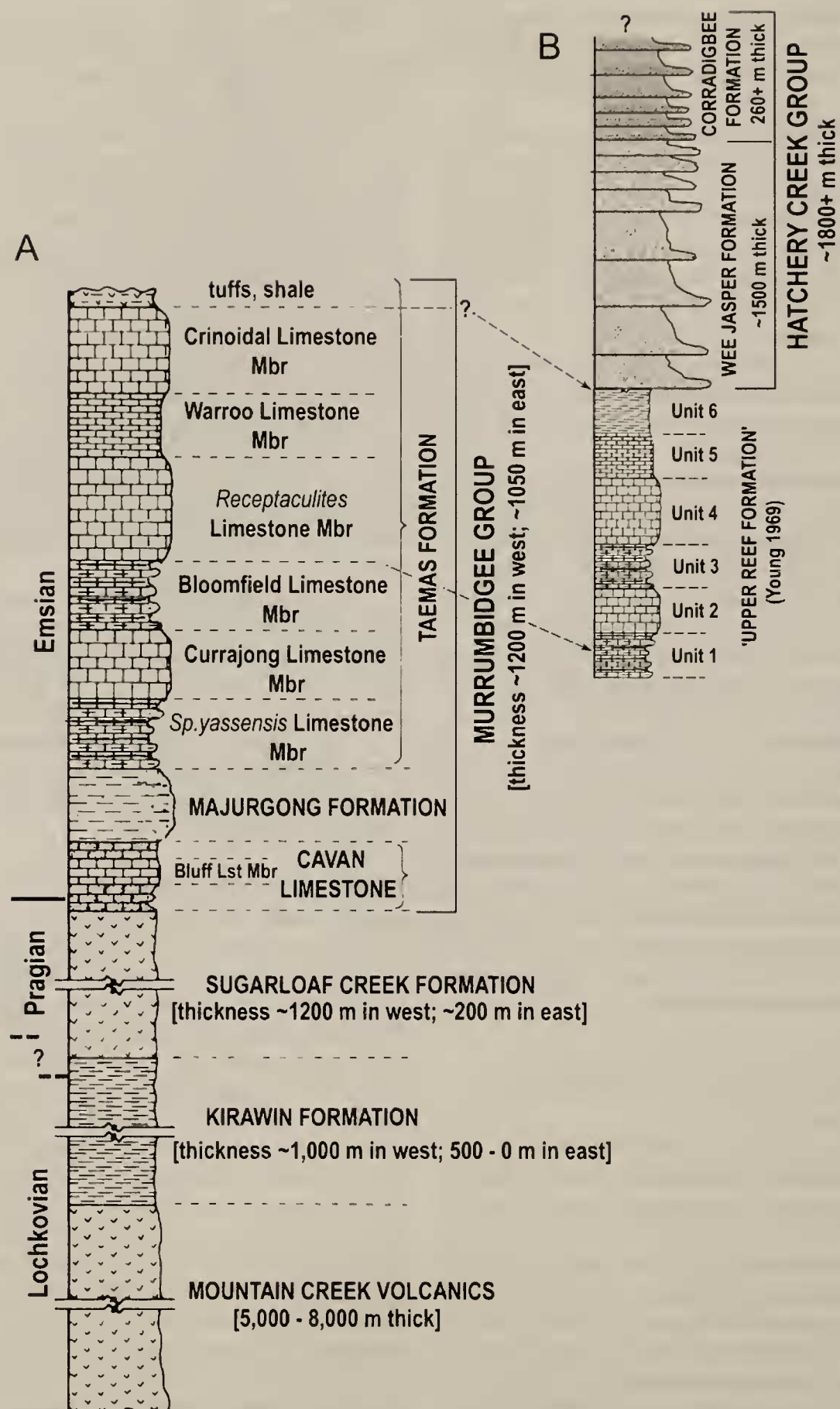
Figure 2. Summary stratigraphic sections (not to scale) for the Devonian sequence of the Burrinjuck area. A. Complete section beneath and through the eastern limestone outcrop (Good Hope – Taemas – Cavan); stratigraphic thicknesses from Owen and Wyborn (1979). B. Upper part of the Murrumbidgee Group and overlying Hatchery Creek Group in the Wee Jasper area; stratigraphy from Young (1969) and Hunt and Young (2010).

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dramatically to the east, partly or entirely due to faulting, and is very thin or absent in the Cavan area. The Kirawin Formation is some 500 m thick in its central exposure (including the designated type section, a road cutting on the Yass-Wee Jasper Road near the valley of Narrangullen Creek; Owen and Wyborn 1979, p. M304). Thickness increases to the west to about 1 km towards Wee Jasper. The Kirawin Formation has conformable and gradational boundaries with both the Mountain Creek Volcanics and Sugarloaf Creek Formation. The lower boundary comprises thin rhyolite and tuff interbedded with black mudstone over several tens of metres (Owen and Wyborn 1979, p. M305).

A fossil locality of the probably terrestrial arthropod (?myriapod) *Maldybulakia* (see Edgecombe 1998a, b), found by Nazer (1970) near 'Brooklyn' Homestead along Sawyers Gully Road, occurs at the lower boundary with the Mountain Creek Volcanics. Owen and Wyborn (1979, p. M305) erroneously referred to these as 'unidentified trilobites', and therefore incorrectly suggested a marine environment for part of the Kirawin Formation.

Sugarloaf Creek Formation

The name 'Sugarloaf Creek Tuff' was first used by Edgell (1949) for the unit underlying the limestones at Wee Jasper. The designated type section (Owen and Wyborn 1979, p. M306) follows the Yass-Wee Jasper Road to the east of Wee Jasper. They interpreted the lithology as derived from erosion of volcanic rocks, mainly coarse, poorly sorted arenite with a series of mudflows in a subaerial environment in the west, changing to better sorted arenite, siltstone and shale with predominantly fluviatile deposition in the east. The thickness varies from about 1200 m near Wee Jasper to about 200 m in the Cavan area, where underlying rhyolites are interpreted to indicate terrestrial deposition.

An important fossil locality in the Cavan area discovered by ANU geology students in the late 1960's produced remains of the millipede-like arthropod *Maldybulakia angusi*, described as the oldest land animal known from the Gondwana supercontinent (Edgecombe 1998a). The outcrop, attributed to the Sugarloaf Creek Formation, lies to the east of Mountain Creek Road, about 3 km to the north of 'Kirawin' Homestead. Geological maps of the area show one or more fault contacts against the underlying Mountain Creek Volcanics (Owen and Wyborn 1979; Prihardjo 1989). Another arthropod locality found by Nazer (1970) is better constrained stratigraphically, and clearly much lower in the sequence (base of Kirawin Formation; see above), suggesting that the

stratigraphy and/or structure of the eastern arthropod locality may have been misinterpreted.

Edgecombe (1998b, p. 294) noted the exceptional preservation of the arthropods from the eastern locality, which occurred 'in an abundance rivalled by few fossil myriapod sites'. Recently some vertebrate remains (an incomplete acanthodian fish, and the lower jaw cartilage of a primitive shark) were identified in material from this locality, inviting comparison with similar remains from sediments within the Boyd Volcanic Complex on the NSW South coast (see Young 2007), from which a different species of the same arthropod genus was described by Edgecombe (1998a, b). The shark lower jaw closely resembles that of *Antarctilamna* Young, 1982 from the Bunga Beds, a black shale lithology (associated with volcanics) which has also produced articulated acanthodians (Burrow 1996). Apart from isolated teeth and scales, the likely Lochkovian age of the Mountain Creek Road locality makes this shark jaw the oldest known fossil preservation in the world of the chondrichthyans (cartilaginous fishes – sharks, rays and chimaeras of the modern fauna).

MURRUMBIDGEE GROUP
Cavan Limestone

The three-fold subdivision of the 'Cavan Stage' described by Browne (1959) comprised a lower 48 m of flaggy limestone, shale, etc., a middle massive 'Bluff limestone' (48 m), and an upper 32 m of thin-bedded limestone. Owen and Wyborn (1979) formalised the name 'Cavan Limestone' because the 'Cavan Bluff Limestone' of other authors could be confused with the more restricted usage of the term 'Bluff Limestone' by previous workers (e.g. Harper 1909, Browne 1959). The nominated type section is under the power lines at Clear Hill in the Cavan area.

Detailed information on the Cavan Limestone in the Cavan area is held in unpublished ANU theses by Koluzs (1972) and Wu (1983). Koluzs (1972) separated off an underlying sequence 44-70 m thick of interbedded siltstones, fine sandstones and shales as the 'Fifeshire Formation', which was incorrectly included by Cramsie et al. (1978) in the upper part of the Sugarloaf Creek Formation. Young (1969) documented a section to the east of Wee Jasper, but named the lower bedded limestones (beneath the 'Bluff Limestone member') the 'Fifeshire member'. Young (1969) defined the base of the formation at Wee Jasper as the first limestone band, a definition followed by Owen and Wyborn (1979) and Mawson et al. (1992, p. 25). Mawson et al. (1992) documented conodont assemblages through a measured section

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177 m thick just south of the section of Young (1969). They identified the Pragian-Emsian boundary at about 35 m below their 'Cavan Bluff Limestone', and 50-60 m above the base of the formation in the Wee Jasper section.

The tripartite subdivision of the Cavan Limestone encompasses a transgression, highstand, and regression, the whole sequence being deposited in a near shore (shallow subtidal to intertidal) environment. Young (1969) recognised detailed similarities at Wee Jasper to the sequence in the Taemas-Cavan area, suggesting either a broad tidal flat, or preservation parallel to a coastline (or both). Owen and Wyborn (1979) commented on the surprising lateral consistency of these lithologies between Taemas and Wee Jasper.

Majurgong Formation

This non-calcareous unit comprises mainly shales and lithic sandstones. Sedimentary structures include cross-bedding and ripple marks. Most of the formation is unfossiliferous, but lingulid brachiopods and gastropods occur in the lower horizons (e.g. bedding planes in the road cutting immediately east of the eastern end of Wee Jasper bridge; lingulids in growth position in shales interbedded with thin limestones in the road cutting opposite the entrance to the Good Hope camping area). These may indicate brackish water conditions, and the Majurgong Formation is interpreted as a non-marine interlude within the predominantly shallow marine Murrumbidgee Group, perhaps deposited in an estuarine environment (Chatterton 1973). Turiniid thelodont fish (agnathans) documented by Basden (1999) were perhaps also restricted to this marginal or non-marine facies.

In the Wee Jasper area the Majurgong Formation is about 120 m thick. It forms a resistant row of hills along the western bank of the Goodradigbee River running north from Wee Jasper village.

Taemas Formation

The Majurgong Formation grades up into the lower fossiliferous beds of the *Spirifer yassensis* Limestone Member, the lowest of six members of the Taemas Formation as recognized and mapped by Browne (1959) in the eastern limestone outcrop (Good Hope – Taemas – Cavan area). Like the Bloomfield Limestone Member, the *Spirifer yassensis* Member comprises interbedded limestones and calcareous shales, and tends to have recessive outcrop compared with the more massive limestones of the overlying Currajong and *Receptaculites* Limestone Members, which both display small reefal bodies in

the Goodradigbee valley. Similar massive beds of the *Receptaculites* Limestone Member occur in the eastern limestone outcrop near Taemas-Good Hope (Chatterton 1973).

The Taemas Formation in the Goodradigbee valley is somewhat thicker (1000-1100 m) than in the east (~800 m). Young (1969) only recognized equivalent members up to the Bloomfield Limestone, the *Receptaculites* Limestone and higher members being much more massive, and designated as the 'Upper Reef Formation', which was subdivided into six units (Fig. 2B). Subsequently, a distinct band of *Receptaculites australis* was mapped by Basden (2001) and Lindley (2002), indicating equivalence in part to the *Receptaculites* Limestone Member as identified by Browne (1959). Overlying massive beds composed largely of crinoid ossicles, some showing faint cross-bedding, presumably correspond in part to the Crinoidal Limestone Member of the eastern outcrop.

The uppermost Unit 6 of the 'Upper Reef Formation' of Young (1969) comprises finely laminated unfossiliferous limestones grading through calcareous shale into coarser lithologies of the non-marine Hatchery Creek Group. Campbell and Barwick (1999) measured a section through the contact, and interpreted the uppermost 110 m of thin-bedded limestones and shales 'as an intertidal zone carbonate deposit consistent with the fact that the overlying unit is the fresh water Hatchery Creek Formation' (p. 125). Lindley (2002, fig. 4) presented a revised version of this section, and Campbell et al. (2009, p. 62) noted that the top of carbonate sequence with shallow marine algal mats was 'transitional into the overlying fresh water Hatchery Creek Formation'.

HATCHERY CREEK GROUP

The 'Hatchery Creek Conglomerate', first named by Joplin et al. (1953), was originally assumed to be Upper Devonian, by lithological comparison with the Hervey Group of central NSW, and thus unconformably overlying the Lower Devonian limestones. The lower conglomerates, sandstones and mudstones form fining-upward cycles which are laterally extensive and traceable over several kilometres along the length of the western escarpment of the Goodradigbee Valley (Young 1969).

A new fossil fish assemblage, discovered during geological mapping by Owen and Wyborn (1979), included such forms as the placoderm *Sherbonaspis hillsi*, which closely resembled the 'winged fish' first documented by Hugh Miller (1841) from classic Middle Devonian Old Red Sandstone fish faunas of Scotland. The assemblage was described by Young

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and Gorter (1981) as demonstrating a probable Eifelian (Middle Devonian) age, rather than Late Devonian as previously assumed. It was suggested that any disconformity with the underlying limestones was of short duration (Owen and Wyborn 1979; Young and Gorter 1981). Previously, Edgell (1949) had interpreted a conformable boundary between the Hatchery Creek sequence and the underlying limestones, whereas Young (1969) and Pedder et al. (1970) had interpreted a disconformable boundary. As noted above, measured sections through new exposures now clearly indicate a gradational boundary at the northern end of the Wee Jasper valley (Campbell and Barwick 1999, Hunt and Young 2010).

Owen and Wyborn's (1979) estimated total thickness of at least 2900 m erroneously included repetition of beds on both sides of the axis of a broad syncline. The revised stratigraphy of Hunt and Young (2010) has elevated the 'Hatchery Creek Conglomerate' to stratigraphic group status, with two constituent formations, the lower Wee Jasper Formation with an estimated thickness based on air photos (at an average dip 40°) of about 1500 m, and an upper Corradigbee Formation at least 260 m thick.

For non-marine basins in various tectonic settings, sedimentation rate has been estimated to vary in the range 0.1-0.6 mm/year (averaged over 10^6 years; Miall 1978). For a total thickness of about 1800 m, the entire Hatchery Creek sequence could have been deposited in about 4.5 Ma using an average sedimentation rate of 0.4 mm/year, or about 5.4 Ma given a slower rate (0.335 mm/year) as documented in some humid fan alluvial systems. This is less than the duration of the *serotinus* conodont zone based on the latest Devonian timescale calibrations of Kaufmann (2006). Thus, it is possible that the Hatchery Creek sequence could have been deposited mostly or entirely within the Emsian stage of the Early Devonian, particularly when there is some evidence that the highest conodont occurrences in the underlying limestone may be low in the *serotinus* zone (Basden 2001; discussed by Young 2004a, pp. 47-48).

Wee Jasper Formation

Owen and Wyborn (1979, p. M314-M320) designated a 1200 m type section of cycles of 'conglomerate, sandstone and siltstone typical of the lower part of the formation' along Cave Creek Road. Hunt and Young (2010) defined an additional type section along 'Windy Top Trail' to include the upper part of the formation. At least 12 major fining upward cycles have been mapped, decreasing in thickness and sediment coarseness up the sequence.

The depositional environment was interpreted by Owen and Wyborn (1979) as a meandering stream deposit, with coarse basal beds probably indicating a high-energy environment and steep gradient. Extensive development of soil profiles suggested that areas were quiescent for long periods before later deposition, with well-developed vegetation being extensively churned in the sediments. Recently discovered are soil horizons with deep root traces (~1.4 m) that are significantly older than recorded elsewhere. In Northern Hemisphere Devonian sequences of this age only low vegetation occurred, and deep root systems did not appear until the Late Devonian after the first forests had evolved (Algeo and Scheckler 1998). However forests may have evolved much earlier on the Gondwana supercontinent (e.g. Retallack 1997).

Corradigbee Formation

Named after the property (*Corradigbee*) that encompasses most of its outcrop (Hunt and Young 2010), the predominant grey-black mudstones of the Corradigbee Formation indicate a change from a well drained to swampy (rather than lacustrine) conditions. Fifteen fining-upward sedimentary cycles are identified in a thickness of at least 260 m (uppermost beds obscured by Tertiary basalt). Numerous new fossil fish localities were identified throughout the Corradigbee Formation (Hunt 2005, 2008), including several new taxa (Young et al. 2010, Hunt and Young 2011), in addition to significant plant remains (lycopsids, stems, early leaves much older than elsewhere; Beerling et al. 2001, Osborne et al. 2004), possible arthropods, and the oldest freshwater gastropod recorded from the Australian fossil record.

EXCEPTIONAL FOSSIL FISH PRESERVATION – THE LONDON CONNECTION

The Rev. W.B. Clarke (1878) was the first to record fossil fish remains from the Burrinjuck area (a bone in limestone collected by Hamilton Hume, and a fish spine sent to Sir Philip Egerton in Britain; see Moyal 2003, p. 1138). The discovery of a fossil lungfish skull near old Taemas Bridge on the Murrumbidgee River (by C.A. Sussmilch of Sydney Technical College) was reported by Etheridge (1906), being the oldest known example at the time of this major group (represented in the modern fauna by only three genera, one of which is the Australian lungfish *Neoceratodus*). The significance of the Taemas skull resulted in it becoming the holotype of a new genus *Dipnorhynchus*, erected by the German authority Prof. Otto Jaekel (1927), and described in
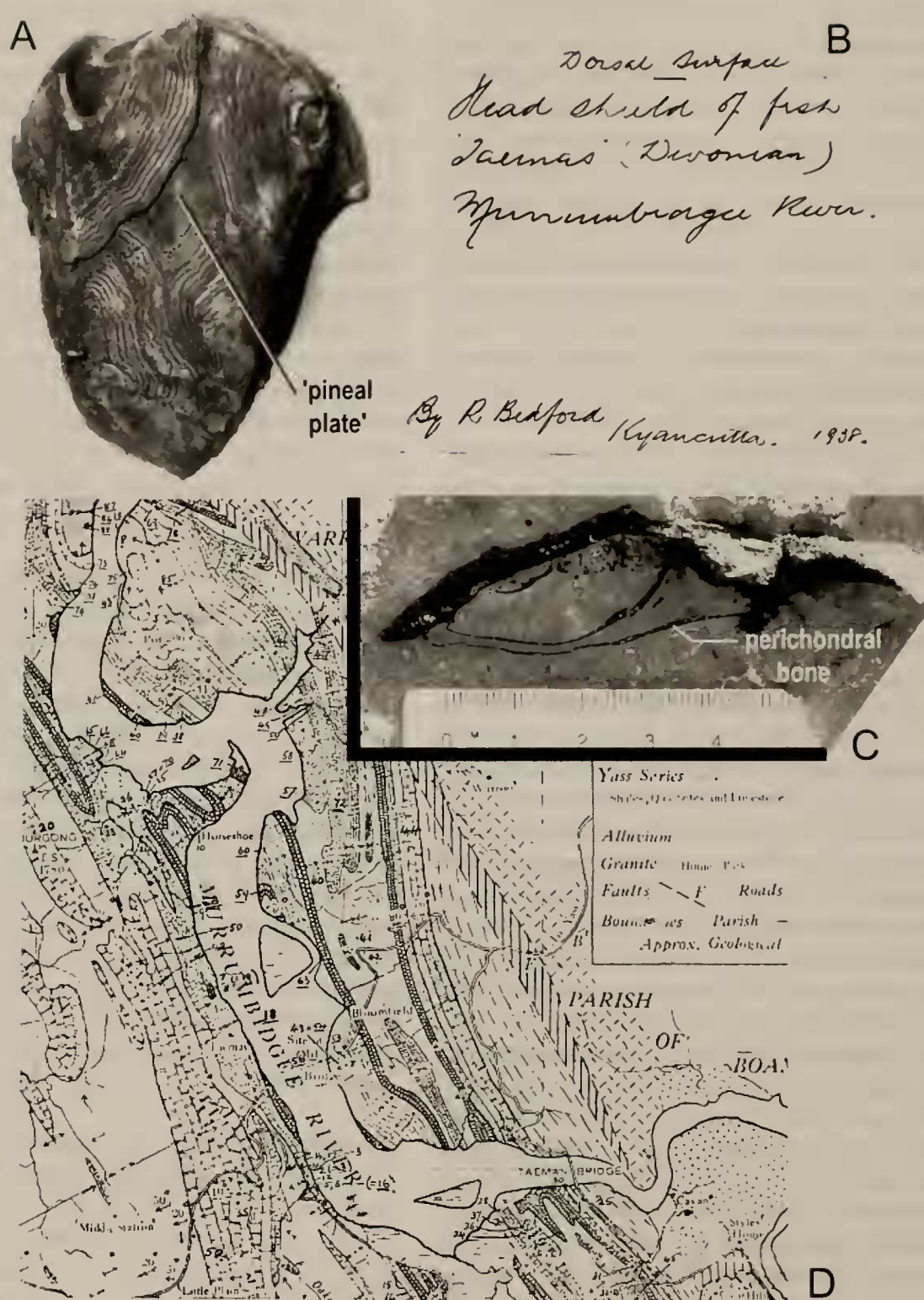
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Figure 3. A. 1938 photograph of a presumed Devonian fish skull with a central 'pineal plate' sent by Robert Bedford, Director of the Kyancutta Museum, SA (covering letter dated October 21, 1938) to the collector, Mr W.E. Williams of Cootamundra, NSW. B. Annotation on the back of the photograph. The original of this letter, accompanying sketches and photograph, are held in the ANU Palaeontological Collection with a cast of the specimen – now BM P27073, the holotype of *Williamsaspis bedfordi* White, 1952 housed in the Natural History Museum, London. C. Bone (dark colour) weathering out of clean limestone, observed in the outcrop near Cooradigbee Homestead (see Fig. 1C). The lower thin black lines represent surface ossification of internal cartilage (perichondral bone), an exceptionally rare preservation type that motivated the British Museum to spend over 4 months of intense fossil collecting in the Burrinjuck area (1955, 1963). D, portion of the draft geological map provided by Dr Ida Browne for use by Mr H.A. Toombs in the 1955 and 1963 British Museum collecting expeditions, with his fossil fish localities marked.

more detail by Hills (1933, 1941). Harper (1909) also recorded some 'fish plates' in the limestones, and a Burrinjuck fossil fish skull collected by Mr J.A. Watt, a student at Sydney University, was sent by the NSW Government Geologist to London for examination by the leading British fossil fish expert (Sir) Arthur Smith Woodward. This was exhibited in 1916 to the Geological Society in London, and described 25 years later as *Notopetalichthys hillsi* Woodward, the first formal description of a placoderm fish from Burrinjuck (Woodward 1916, 1941; holotype returned to the Australian Museum, AM F45251).

The key event for international recognition of the Burrinjuck fossil fishes was the transmittal to London in 1939 by Robert Bedford (or Buddicom, 1874-1951), Director of the Kyancutta Museum, S.A., of five fossil fish specimens found in the Burrinjuck area by local collectors A.J. Shearsby (Yass) and W.E. Williams (Cootamundra). They came from two localities (White 1952): 'Barber's ... on the Goodradigbee River' (now the 'Cooradigbee' property; the area nominated for heritage listing), and 'Taemas on the Murrumbidgee River'. These specimens (see Fig. 3A) were used in the laboratories of the British Museum (Natural History) by Mr H.A. Toombs to develop a method of extracting fossil bone from limestone using acetic acid (Toombs 1948). This is now a standard technique used throughout the world, for example to extract fossil mammals from limestones at the World Heritage Riversleigh site in Queensland.

The five Burrinjuck specimens sent to London were described in a 53 page monograph by White (1952), only the second scientific publication describing fossil bones extracted by this new technique. White noted that the Burrinjuck specimens were 'even more interesting and important than first supposed', because braincase structures were preserved (see Fig. 3C), which could be acid-extracted for the first time. These uniquely preserved type specimens remain in the British Museum in London (now called the Natural History Museum).

As a direct result of White's (1952) publication, the British Museum (Natural History) sent H.A. Toombs to Australia on two expeditions (1955, 1963) specifically to collect more fossil fish from the Burrinjuck area. Some 560 fossil fish samples collected from 139 different sites (Fig. 3D) were transported back to London, where they remain in the research collections of that major institution. In his internal reports (Toombs 1955, 1964) Toombs noted for the 1955 expedition that the area needed protection, and he wrote that he had advised the 'Australian authorities ... to discourage casual collecting', but

there was no action to effect this in the ensuing fifty-five years. The heritage application lodged in March, 2010 should partly address the need for protection of this unique type of fossil vertebrate preservation.

In his 1963 report Toombs recorded visits to universities in Sydney and Canberra, noting that neither university had any fossil fish specimens, which 'boosted the morale' because the London museum thus had the only substantial collection. He visited the new ANU Geology Department in Canberra only after the bulk of collected samples had already been consigned to London (Prof. K.S.W. Campbell, *pers. comm.*). ANU Foundation Professor of Geology D.A. Brown was extremely concerned that so much fossil material had been removed without local knowledge. Prof. E.S. Hills FRS (University of Melbourne) sent a letter of protest to Dr Errol White, a Fellow of the Royal Society and Keeper of Palaeontology at the British Museum. The best specimens were eventually described many years later (White and Toombs 1972; White 1978). At the time of collection there had been no consultation with local scientists, and hence no agreement about repatriation of Burrinjuck type specimens, in contrast to later collecting by the Natural History Museum at Gogo, WA (see Long 2006).

The discovery of an excellent new specimen of the lungfish *Dipnorhynchus* near the Shearsby's Wallpaper site in the Taemas area initiated a research program on early vertebrates at the Australian National University in Canberra (Campbell 1965; Thomson and Campbell 1971). Numerous subsequent papers and monographs, by Campbell and Barwick (1982-2007) and others, document some of the oldest known and best preserved fossil specimens of the Dipnoi (lungfishes; see Fig. 4F). In addition, a large collection of placoderm fish specimens was obtained by ANU from Cave Flat during the 1968 drought, and since then, regular search of outcrops whenever low water levels produced exceptional exposures of clean limestone (see Kellett 2010, p. 37), has resulted in the unequalled collection of such material at the ANU. The placoderms have been documented by Young (1969-81, 1985-86, 2003-05, 2008-10), Long and Young (1988), Findlay (1996), Goujet and Young (2004), Mark-Kurik and Young (2003), and Young et al. (2001a, b, 2010). Other fish groups (osteichthyans, acanthodians, microvertebrate remains etc.) are documented by Basden (1999, 2001), Basden et al. (2000a, b), Basden and Young (2001), Burrow (2002), Burrow et al. (2010), Giffin (1980), Long (1986), Lindley (2000-2002), Ørvig (1969) and Schultze (1968).

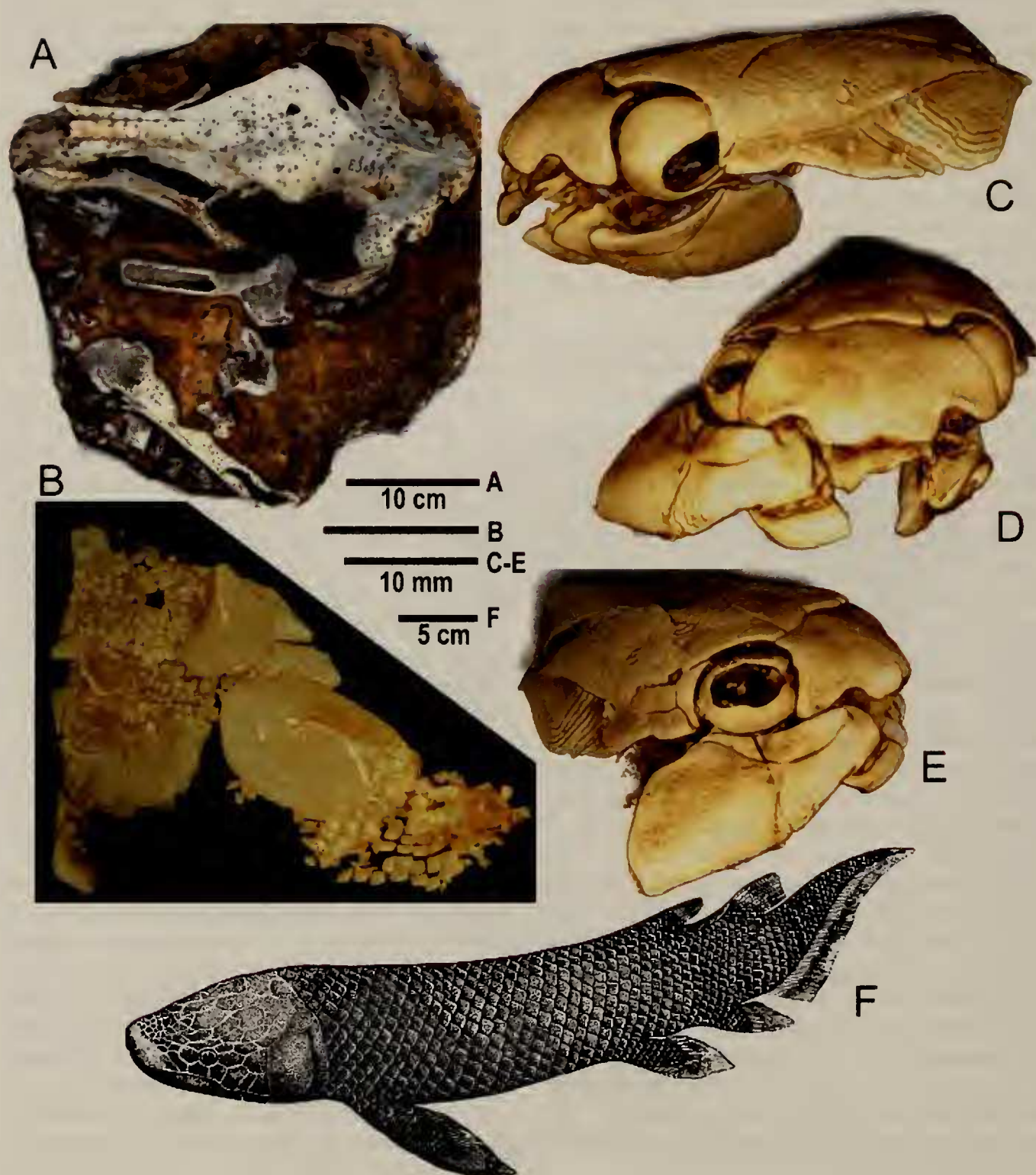Proc. Linn. Soc. N.S.W., 132, 2011

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Figure 4. A. An enormous skull of *Thylacinus cynocephalus* (AM F340) collected from cave deposits at Cave Flat by R. Etheridge Jnr in 1888, said to be the largest known (Etheridge 1889, 1892). B-E, CT scanning images of new genus and species of Early Devonian arthrodire placoderm, ANU 49384, showing portion of the tail (B), and complete skull, rostral capsule, both eye capsules, jaw cartilages and toothplates in approximate life position (C, left anterolateral view; D, anterior view; E, right lateral view). F, Generalised reconstruction (by Dr R.E. Barwick) of a primitive lungfish from the Burrinjuck limestones.

The extinct placoderms, which lacked true teeth (Young 2003), are perhaps the most primitive of all the jawed vertebrates, and were by far the most diverse and widespread Devonian fish group (Young 2010). They provide unique insights into braincase structure at the time jaws first evolved. No other fossil locality in the world compares with Burrinjuck regarding the diversity of forms with the braincase preserved (see Faunal List; Appendix). Exceptional specimens include a perfectly preserved 'eye capsule' (Fig. 5A) that completely enclosed and surrounded the soft tissues of the eye, revealing intricate internal details including nerves and muscle attachments controlling eye movement, and tubules connecting the optic nerve and associated blood vessels to the retina (Young 2008a, b). No comparable specimen exists in any other museum collection, and the XCT scanned image of this specimen has been displayed at various international venues including London (Optometry and Vision Science Research Symposium, College of Optometrists), the Horizon Planetarium in Perth, and the Fels Planetarium, Franklin Institute, Philadelphia. Many tens of thousands of Devonian placoderm specimens are held in museum collections all over the world, but only a very few examples display the entirely extracted skull and braincase, eye capsules, jaw cartilages and toothplates. All such specimens come from the Burrinjuck area, and are housed at the Australian National University in Canberra (see Fig. 4C-E, 5B).

ANCIENT REEF EXPOSURES IN THE GOODRADIGBEE VALLEY

During Late Silurian – Early Devonian time much of eastern Australia was a shallow tropical sea, as indicated by widespread coralline limestone deposits. However, in most areas the rocks are folded or otherwise deformed, and poorly exposed, so actual coral reefs generally cannot be seen. Where exposed, their fossil content can be studied by acid cleaning one metre square 'windows' of typically weathered limestone surfaces in a grid across the outcrop, to attempt a reconstruction of the different facies of a fossil reef system.

Following construction of Burrinjuck Dam, large areas of limestone were submerged, and washed completely clean and slightly etched by the lake water. Extreme fluctuations of water level during droughts associated with climate change in recent decades have produced exceptional exposures of ancient coral reefs in the lower Goodradigbee valley (Fig. 6). The integrity of the reef structures is enhanced by the fact

that the limestone strata are relatively undeformed compared to the folded strata of the Taemas-Cavan area.

At least seven reefal structures up to 1 km long and 80-100 m thick were identified by Young (1969). Away from the lake to the south (e.g. in the vicinity of Cooradigbee homestead and Carey's Cave; see Fig. 6A) the reefs form massive grey limestones with weathered surfaces in which little structure is seen (Fig. 6D). In contrast, spectacular exposures on the lake foreshore like Cathedral Rock and Currajong Reef (Fig. 6B-C) display back-reef deposits of crinoid gardens, colonies of stromatoporoids and corals within the reef in growth position (Fig. 6F), and a fore-reef of rolled coral blocks and debris that accumulated in storms over the ancient reef front (Fig. 6E).

It is acknowledged that the better known 'Great Devonian Barrier Reef' of the Canning Basin in the Kimberley area, WA, is a much larger structure, with spectacular cliff exposures that cannot be matched by the Burrinjuck reefs (see Playford et al. 2009). However, this reefal system is of Late Devonian age, whereas the Burrinjuck reefs represent a significantly earlier episode of reef development. Differential weathering of relatively flat-lying strata in the Kimberley has produced a topography simulating an exhumed reef system, but much of the stratigraphy is hidden in the subsurface, in contrast to the folded stratigraphic sections that are well exposed at Burrinjuck. In addition, rock outcrops generally need to be acid-cleaned in small areas to examine fossil content (see Playford et al. 2009, p. 97), so the various animal associations on the reef system cannot be observed in detail across an entire reef exposure, as can be done at Wee Jasper. All of these features make the Devonian reefs in the lower Goodradigbee valley amongst the most spectacular and scientifically significant ancient reef exposures known.

OLDEST KNOWN CORAL REEF FISH FAUNA

Australia's renowned World Heritage Great Barrier Reef is notable for its exceptional tropical fish diversity. It is relevant therefore that the exceptionally diverse Burrinjuck fossil fish fauna is also the world's oldest known coral reef fish assemblage. A much younger fossil fish occurrence (Molte Bolca, Italy, ~50 million years old) was claimed in the journal *Coral Reefs* as the oldest (Bellwood 1996), but this was challenged because there was no 'direct evidence that a coral reef existed in the immediate vicinity of the soft sediments in which the fossils were buried' (Robertson 1998, p. 184-85). In the Wee
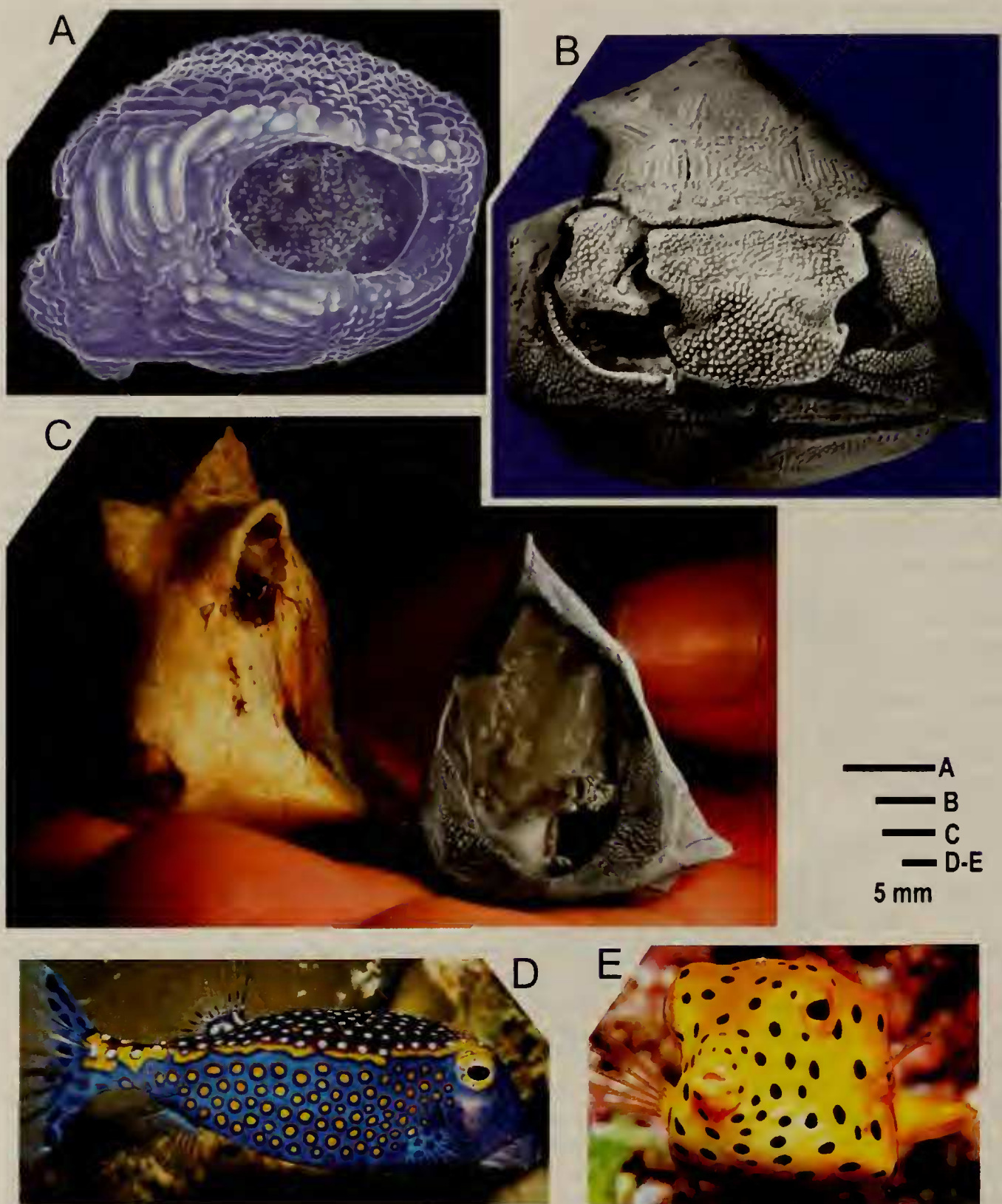
Figure 5. A. CT scanning image of the isolated left eye capsule of the placoderm *Murrindalaspis* (specimen found near Taemas bridge), the oldest known perfected preserved vertebrate eye capsule (specimen in ANU collection; described by Long and Young 1988, Young 2008a, b). B. Completely preserved arthrodire skull, braincase, and jaws in anterior view (from 'Shearsby's Wallpaper' near Taemas; ANU V244, described by Young et al. 2001b). C. Holotype of the williamsaspid arthrodire *Elvaspis tuberculata* Young, 2009 compared (on the right side) with a juvenile turretfish *Tetrasomus* sp. (family Ostraciidae), and two species of Ostracion from the Great Barrier Reef (D, *O. meleagris*; E, *O. cubicus*). D, E, reproduced with permission from Randall et al. (1990).

Figure 6. A. Location of some reef structures identified by Young (1969) from the vicinity of Carey's Cave north to the bed of Lake Burrinjuck (Currajong Reef). Base map a composite of Google Earth images. Reefs 1-3 occur in Unit 2, Reefs 4, 6 in Unit 4, and Reef 5 in Unit 5 of the 'Upper Reef Formation' of Young (1969). B, 'Cathedral Rock', a massive reef limestone washed completely clean ⌄y the waters of Lake Burrinjuck (Dr A. Basden, Macquarie University, in foreground). Cave deposits of uncertain age in some of the rock crevices have produced skeletal remains including *Thylacinus* (J. Caton, I. Cathles, pers. comm.). This outlier (completely submerged at high water level) is about 200 m along strike to the north from Reef 1. C, view from northwest to Currajong Reef on the lakebed at low water level, March 2010. D, Reef 2, immediately north-west of 'Cooradigbee' homestead, represented by massive limestone (right side of image), with bedded limestone (left side of image) wrapped around the reef by compaction of the sedimentary sequence. The limestone shows normal dark grey weathering, in which few structures are visible without special treatment by acid or thin sectioning of rock samples. E. Bedded limestone outcrop adjacent to F, showing numerous rolled corals with random growth orientations (talus that accumulated off the reef front due to wave action or storms). F, Dr A. Basden, Macquarie University, demonstrating upward growth of massive coral colonies (white arrow), in situ within the massive limestone forming the core of Currajong Reef.

Jasper valley, the evidence that the fish preserved as fossils lived in and around coral reefs is unequivocal. In the Currajong Reef, fossil bones are associated with diverse coral colonies within the reef structure; sometimes bones are observed in outcrop forming the site of growth for coral colonies (Fig. 7A). The ANU collection of acid-etched specimens has numerous examples where bones and skulls show small corals still attached that grew from their surfaces (Fig. 7B). At the time of deposition the limestone was soft calcareous mud, and the disarticulated skeletons of dead fish provided very localised hard substrates on which coral larvae could settle. In some specimens

the original orientation of the bone, and how deep it was buried in the mud, can be reconstructed from the pattern of small corals encrusting its surface.

BIODIVERSITY HOTSPOTS IN TROPICAL REEF FISHES - DEVONIAN vs RECENT

It is well documented that peaks in modern tropical fish diversity are associated with coral-rich areas. That this also applied in the Palaeozoic is evidenced by ongoing research revealing many new forms with different body shapes to occupy a variety

Figure 7. A. Placoderm bone (dark colour) projecting from the limestone outcrop at Currajong Reef, on which coral/algal encrustations show upward growth patterns (at the time of deposition the rock was soft calcareous mud, and the bone a hard surface on the sea bottom on which coral larvae could settle). B. lower toothplate (infragnathal bone, ANU V3081) of a filter- feeding homostiid arthrodire (cf. *Cavanosteus* Young, 2004). C. Display in the Geological Museum of St. Petersburg University, Russia, of the giant arthrodire *Heterostius* from the early Middle Devonian of the Baltic sequence (bones exceeding 1 metre in width).

of ecological niches on the Burrinjuck tropical reef system (Young 2009). Unpublished data from many new specimens (Appendix) demonstrates that the Burrinjuck fish fauna (at least 70 species) is more diverse than any other Devonian fossil fish site in the world. Direct comparisons can be made with reef fish diversity (also mainly placoderms and lungfish) at the famous Gogo fossil locality, also one of the most diverse known Devonian fish assemblages (some 55 species; Long and Trinajstic 2010).

Two issues concerning tropical reef fish diversity in the Devonian compared to modern reefs have been discussed in the recent scientific literature. Anderson (2008) analysed lower jaw elements to compare the diversity of 'coccosteomorph' arthrodire placoderms from the Gogo reef assemblage with 'pachyosteomorph' arthrodires from the younger (Famennian) Cleveland Shale assemblage (Ohio USA). He found the former to show less diversity than the latter, and concluded that in Devonian oceans highest diversity levels may have occurred in open basin fish faunas, the complete opposite of modern oceans where greatest biodiversity occurs on reefs.

Two problems with Anderson's comparison concern the different age of the Gogo (Frasnian) and Cleveland (Famennian) assemblages, and the fact that palaeogeography was not considered. Many of the giant Cleveland fish taxa also occur in limestones in Morocco (e.g. Lehman 1956, 1976, 1977), evidently deposited on a shallow shelf close to a reef environment, and north Africa was much closer to eastern North America than today (the Atlantic Ocean did not open until the Mesozoic).

To reliably assess 'basin' versus 'reef' fish diversity in Devonian oceans the compared localities should be the same age, and clearly representing completely different facies. Thus, the Burrinjuck coral reef fossil fish fauna can be compared with the famous Early Devonian fossil assemblage from the Hunsrückschiefer of Germany, a marine black shale deposit also of Pragian-Emsian age. The Hunsrückschiefer has produced numerous invertebrate fossils including *Receptaculites*, which gives its name to the *Receptaculites* Member of the Taemas Limestone at Burrinjuck. The Hunsrückschiefer fish fauna includes one lungfish species originally assigned to the Australian genus *Dipnorhynchus*, and later provisionally referred to the closely related *Speonesydrion* from Burrinjuck (Campbell and Barwick 1984a). More preparation of the holotype specimen has led to its placement in a new but closely similar genus *Westollrhynchus* by Schultze (2001). *Lunaspis* is a well-known petalichthyid placoderm from the Hunsrückschiefer (e.g. Young 2010, fig. 3e-

f) that is also recorded from Burrinjuck (Young 1985). The largest arthrodire from the Hunsrückschiefer is *Tityosteus rieversi*, probably a member of the family Homostiidae, also represented at Burrinjuck by *Cavanosteus* (e.g. Young 2004). These faunal similarities validate a biodiversity comparison between the two localities.

The total fish diversity recorded so far from the Hunsrückschiefer is 14 genera and 15 species, dramatically less than at Burrinjuck, even though fossils from the famous German deposit have been collected and studied scientifically for about 150 years (Bartels et al. 1998). There are nine placoderm genera and 10 species known from the Hunsrückschiefer, of which only three genera and species are arthrodires. This compares with at least 40 genera and 45 species at Burrinjuck, including some 30 arthrodire species (Appendix). These data strongly suggest, in contrast to the conclusion of Anderson (2008), that in Devonian oceans the peaks in fish biodiversity were associated with tropical reef environments, just as in modern oceans.

Young (2009, 2010) discussed the fact that the highly diverse Devonian placoderms could be compared with the dominant teleosts of the modern fish fauna. Taking taphonomic factors into account, there is no evidence to indicate lower diversity of reef fishes on Devonian compared to modern reefs as far as supraspecific taxa are concerned. Anderson (2008, p. 967) suggested no fish on modern reefs of comparable size to the giant Devonian predator *Dunkleosteus*, but very large sharks, both predatory (e.g. 6-7 m tiger shark *Galeocerdo cuvier*) and filter feeders (12+ m whale shark *Rincodon typus*) occur on and around modern tropical reefs. The very large arthrodires of the latest Devonian are consistent with 'Cope's rule' of evolutionary size increase, and even the largest known Early Devonian arthrodires (e.g. *Tityosteus* from Germany, *Dhanguura* from Burrinjuck) probably attained only several metres total length (Young 2004). But by the early Middle Devonian enormous arthrodires including probable filter-feeders such as members of the family Homostiidae had evolved, with earlier representatives known from Burrinjuck (Fig. 7B-C).

Regarding species diversity, many modern fish species can be readily distinguished by differences in surface colour and pattern, and many reef teleosts are brightly coloured. The williamsaspid arthrodires from Burrinjuck have similar body shape to modern boxfishes (family Ostraciidae), interpreted by Randall et al. (1990) to comprise nine species in four genera, most of which are instantly recognisable by their bright colours (Fig. 5D-E). Even amongst the generally

drab sharks and rays, numerous similarly-shaped species are easily distinguished by different colours or distinctive surface markings or patterns (see Last and Stevens 1994). Such information is unavailable for fossil fish, even with exceptional whole body preservation such as occurs in the Hunsrückschiefer of Germany. For these reasons, fish diversity at the species level in the fossil record is probably greatly underestimated (Young 2010, p. 542).

The highly diverse Burrinjuck fossil fish assemblage can be compared with some other noteworthy Devonian fossil fish sites. Miguasha National Park in Quebec is a World Heritage listed Devonian fish locality. Many thousands of exquisite fossil fish have been collected, but they are preserved as partly compressed whole bodies in siltstones, and can only be extracted by manual preparation. Numerous Miguasha specimens are held in museums throughout the world, including such famous forms as the lobe-fin *Eusthenopteron*. Even so, Miguasha has produced no more than 21 fish genera in total (Schultze and Cloutier 1996). Similarly, the well known Canowindra fossil fish site in central NSW has produced several thousand fossil fish specimens, but only eight fish genera and species are known. In addition, although generally preserved as relatively complete impressions in sandstone, their internal structure is largely unknown. Gogo, WA, is the only other site in the world producing acid-extracted fossil fish specimens in a comparable diversity to Burrinjuck (~51 genera; Long and Trinajstic 2010). Gogo, Canowindra and Miguasha are all of similar age, and the fossil fish from all three sites are more highly evolved than at Burrinjuck which is 20-30 million years older. In particular, the most diverse component of these faunas (placoderms) have lost much of their internal ossification in the Gogo species. Thus, braincase preservation is a very special attribute of the many primitive forms known only from Burrinjuck. It should be noted that in the first monograph describing placoderms from Gogo (Miles 1971), a Burrinjuck specimen was essential for interpretation of placoderm nasal structure, even though there were numerous exquisitely preserved remains of a new Gogo species of the genus *Holonema* (see Miles 1971, figs. 104, 105).

SOME OUTSTANDING ISSUES

Site protection vs. agricultural activities

Heritage protection of a nominated area only relates specifically to the heritage values of that area, but landowners may still have concerns about possible restrictive impacts on agricultural and other activities. A statement of 'principles of engagement for Heritage Listing', prepared by Helen and Ian Cathles (owners of *Cooradigbee* and *Cookmundoon* stations in the Wee Jasper valley) to clarify rights of landowners, was submitted with the 2010 Heritage Nomination. The four main points may be summarized:

i) the nomination specifically included only fossiliferous outcrops and caves within the nominated area;

ii) the opportunity to integrate successfully conservation with agriculture was recognized, but 'without fear of loss of enterprise and personal infrastructure' where the heritage nominated area (as in this case) includes landowners' paddocks containing fossiliferous outcrops. In such agricultural areas surrounding these outcrops the continuation of essential agricultural activities such as 'bushfire hazard, weed control, feral animal control' would need to be guaranteed.

iii) past practice for the 'identification and preservation of these fossil outcrops' of national significance to be continued;

iv) differences from 'significant impact guidelines' (clause 1.1, Environmental Protection and Biodiversity Conservation Act 1999, p. 21) were noted – specifically, the fact that fossil specimens identified as significant would gradually deteriorate and disappear without intervention. Hence there is a special requirement for expert removal and preparation of fossil specimens, and their subsequent responsible care and housing in appropriate storage to ensure their preservation for posterity.

Collections support and protection

The point just stated focuses on potential incompatibility between protection of actual outcrops, and removal of fossils by various extractive processes that could be considered to damage such outcrops. In this case the scientific significance of specimens (and their enhanced heritage value) can be realized only after their removal for scientific preparation and study. This process greatly increases their information content, but in the case of acid-prepared Burrinjuck braincase material also produces scientific specimens of exceptional fragility, requiring adequate curation, and special care and long-term protection from damage (e.g. Russell and Winkworth 2009).

In these requirements the Burrinjuck fossil vertebrate material can be compared with the Riversleigh-Naracoorte linked World Heritage fossil mammal sites, which have produced some 118 vertebrate species (although from separate limestone and cave deposits of two completely

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different time periods). The Riversleigh specimens are also particularly fragile after acid extraction, and are permanently curated in the Queensland Museum, Brisbane, a recognized collecting institution, with both the tradition and a legal requirement for long-term preservation of its collections.

In contrast, the largest existing collection of Burrinjuck fossil fish material is a university collection housed on the ANU campus in Canberra. University collections in the state capitals all have a state museum or institutional equivalent where collections can be accessed for permanent protection and preservation. This is not the case in the National Capital, where there is no museum that takes responsibility for natural history collections (among countries of the developed world Australia is probably unique in this respect). Accordingly, there is a university policy covering long term management, storage and conservation of significant collections, but minimal funding under current circumstances to achieve this. Unlike some famous universities overseas (Sedgwick Museum, Cambridge; Oxford, Harvard, Yale, University of California; numerous European and Russian universities; see Fig. 7C), there is no museum catering for relevant research materials and collections in any scientific field at the Australian National University. Although the ANU palaeontological collection contains numerous type specimens, is does not currently comply with requirements of some international journals regarding lodgement of types in accordance with requirements of the International Code of Zoological Nomenclature ('in an appropriate permanent institution, with staff and facilities capable of ensuring their conservation and availability for future reference in perpetuity'; quoted from 'Notes for Authors' of The Palaeontological Association, London, publishers of the international journals *Palaeontology* and *Special Papers in Palaeontology*). The geological curator position at the Australian National University was abolished 10 years ago, since when no person has had responsibility to maintain the general fossil collections.

Relevant to this issue is the observation that many other internationally recognized fossil localities, such as the Miguasha (Canada) and Naracoorte (S.A.) fossil World Heritage sites, the Canowindra Devonian fish site in NSW, and numerous examples in Europe, have established Visitor Centres with well-maintained displays and collections. A 'Wee Jasper Visitor Center', including interactive displays, and properly housed and curated on-site fossil collections, is envisaged as an essential future development to make more widely known the scientific significance of the Burrinjuck area. Of course, this would not diminish the scientific requirement that type and figured specimens be properly housed and curated in a recognized institution, to ensure their preservation in perpetuity as part of Australia's scientific and cultural heritage.

Stage II nomination

Negotiation with land-owners covering the eastern limestone outcrop [Taemas-Cavan] to support a 'Stage II' nomination is proposed, based on a successful outcome for the current nomination. The eastern area includes the stratigraphic type sections of all Murrumbidgee Group formations and members, the protected 'Shearsby's Wallpaper' fossil brachiopod exposure, and is historically and scientifically significant for fossil vertebrates, producing the first lungfish skull (the holotype of *Dipnorhynchus sussmilchi* Etheridge), and also holotypes of the placoderms *Taemasosteus novaustrocambricus* White, *Parabuchanosteus murrumbidgeensis* White, and *Shearsbyaspis oepiki* Young. Numerous fossil fish sites within the area were collected by H.A. Toombs in 1955 and 1963 (Fig. 3D). The Stage II nomination would also include the main area of outcrop and type sections for the Hatchery Creek Group to the west of Wee Jasper (areas labelled (II), Fig. 1C).

Repatriation of types from London

As noted above, when the 1955 and 1963 British Museum expeditions removed so much fossil vertebrate material from the Burrinjuck area without local knowledge, it caused great concern amongst Australian palaeontologists, and at least one letter of protest was sent to the British Museum. Probably to make amends, and with the necessity of negotiating with the then director of the Western Australian Museum (Dr David Ride), the 1967 joint British Museum-W.A. Museum expedition to the Gogo fossil fish site in the Kimberley region included an agreement to return type specimens and representative material to Australia. This is now a normal arrangement for scientific palaeontological collecting in most countries that restrict export of significant fossil specimens, as does Australia under the Moveable Cultural Heritage Act.

Repatriation from London of type specimens and representative material of Burrinjuck Devonian fossil fish held by the British Natural History Museum must be placed on the agenda, once the issues of long term protection of existing Australian collections is resolved.

BURRINJUCK AREA FOSSIL FISH SITES

SUMMARY

The Burrinjuck area has both national and international significance, from the fossil vertebrate perspective in the same class as some comparable World Heritage listed sites both in Australia and overseas. Main points of significance include:

i) a unique sequence of sedimentary strata some 5 km thick containing numerous fossil horizons encompassing the final terrestrialization of the earth's biota during the Devonian Period (~418-360 million years ago);

ii) the area has produced (and continues producing) uniquely preserved braincase structures of early vertebrates from ~400 million years ago, in a diversity of forms unequalled in any other fossil site in the world. Their significance remains undiminished in the modern era of molecular biology, the 'notable outstanding specimens … from the Early Devonian of Taemas-Wee Jasper … and … Gogo' (Ahlberg et al. 2006, p. 338) still playing a key role in evolutionary studies (e.g. Friedman and Brazeau 2010).

iii) exceptionally exposed Early Devonian tropical reefs occur in the lower Goodradigbee valley, the massive reef limestones also containing significant karst and cave structures;

iv) Burrinjuck fossil fish represent the world's oldest known coral reef fish assemblage, and also the most diverse vertebrate fauna recorded from any Devonian fossil site in the world (the period called the 'Age of Fishes'); associated are numerous invertebrates including corals, bryozoans, stromatoporoids, brachiopods, gastropods, nautiloids and trilobites, giving a total of some 266 genera of vertebrate and invertebrate fossils documented so far;

v) the area produced five key specimens used in the 1940's in London to develop the acetic acid preparation technique, now standard in laboratories throughout the world for extracting fossil vertebrates from calcareous rock matrix, and it was the target of two collecting expeditions by the British Museum (Natural History) in 1955 and 1963, when some 560 specimens were removed to London.

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APPENDIX

Faunal list for Devonian fossil vertebrates from the Murrumbidgee Group limestones at Burrinjuck, updated from Young (2009, table 1) with additional taxa represented by newly prepared specimens (indicated by ANU V number).

AGNATHA
Thelodontida
1.   *Turinia* sp. cf. *T. australiensis* Basden, 1999
GNATHOSTOMATA
ACANTHODII
2.   *Cheiracanthoides comptus* Giffin, 1980
3.   *Cheiracanthoides* sp. cf. *C. wangi* [Basden, 2001]
4.   *Taemasacanthus erroli* Long, 1986
5.   *Taemasacanthus porca* Lindley, 2000
6.   *Taemasacanthus narrengullenensis* Lindley, 2002a
7.   *Taemasacanthus cooradigbeensis* Lindley, 2002a
8.   *Cavanacanthus warrooensis* Lindley, 2000
9.   *Cambaracanthus goodhopensis* Lindley, 2000
10.   *Nostolepis guangxiensis* Wang, 1992 [Basden, 2001]
11.   *Nostolepoides platymarginata* Burrow, 1997 [Basden, 2001]
12.   *Trundlelepis cervicostulata* Burrow, 1997 [Basden, 2001]
13.   *Gomphonchus? bogongensis* Burrow, 1997 [Basden, 2001]
OSTEICHTHYES
Actinopterygii
14.   *Ligulalepis toombsi* Schultze, 1968
Sarcopterygii
15.   *Onychodus yassensis* Lindley, 2002b
16.   ?osteolepid indet. Lindley, 2002b
17.   porolepiform indet. Young, 1985
Dipnoi
Dipnorhynchidae
18.   *Dipnorhynchus sussmilchi* (Etheridge) Hills, 1941
19.   *D. kurikae* Campbell and Barwick, 1985, 2000
20.   *D.(Placorhynchus) cathlesae* Campbell and Barwick, 1999; Campbell *et al.,* 2009
21.   *Speonesydrion iani* Campbell and Barwick, 1983
22.   *Cathlorhynchus trismodipterus* Campbell, Barwick and Senden, 2009
CHONDRICHTHYES
23.   *Ohiolepis* sp. Ørvig, 1969
24.   *Skamolepis fragilis* Giffin, 1980
PLACODERMI
Arthrodira
25.   *Buchanosteus confertituberculatus* Young, 1979
26.   *Parabuchanosteus murrumbidgeensis* White and Toombs, 1972
27.   buchanosteid n. sp. [ridged ornament] ANU 49387 [skull, braincase]
28.   buchanosteid n. sp. [anterior nasal openings] ANU V2418 [rostral capsule]
29.   *Burrinjucosteus asymmetricus* White, 1978
30.   *Goodradigbeeon australianum* White, 1978
31.   *Taemasosteus novaustrocambricus* White, 1952
32.   *Toombsosteus denisoni* White, 1978
33.   *Arenipiscis westolli* Young, 1981
34.   *Errolosteus goodradigbeensis* Young, 1981
35.   *Williamsaspis bedfordi* White, 1952
36.   *Cavanosteus australis* (McCoy) Young, 2004a
37.   *Cathlesichthys weejasperensis* Young, 2004b
38.   *Dhanguura johnstoni* Young, 2004b
39.   *Bimbianga burrinjuckensis* Young, 2005
40.   ?holonematid n. g. [?*Bimbianga* sp. 2] ANU V2933 [SO plate]
41.   *Elvaspis tuberculata* Young, 2009

42.   *Elvaspis whitei* Young, 2009
43.   small brachythoracid n. g. ANU 49384 [complete skeletons]
44.   brachythoracid n.g. 1'highly arched' (Young, 2009, p. 76) ANU V114 [PNu plate]
45.   brachythoracid n.g. 2 [long para-articular process] ANU V156 [PNu plate]
46.   brachythoracid n.g. 3 [MD contacts vertebral column] ANU V3118 [MD plate]
47.   brachythoracid n.g. 4 [MD rounded carinal process; ANU V1059, 2386, 2403, 35332]
48.   ?heterostiid n.g. [long cheek] ANU V79 [SO plate]
49.   ?*Antineosteus* n.sp. ANU V1970 [SO plate]
50.   ?*Atlantidosteus* n.sp. ANU V2946 [SO plate]
51.   'coccosteid' [lacking median spine] ANU V2899 [MD plate]
52.   'coccosteid' [posterior median spine] sp. 1 ANU V124, 1209, 2447 [MD plates]
53.   'coccosteid' [smooth posterior median spine] sp. 2 ANU V 3244 [MD]
54.   'coccosteid' [no spine; posterior carinal process] ANU V1863 [MD]

Acanthothoraci
55.   *Weejasperaspis gavini* White, 1978
56.   weejasperaspid n.g. [long spinal] ANU V38 [shoulder girdle]
57.   *Brindabellaspis stensioi* Young, 1980
58.   brindabellaspid n.g. [with spines] ANU V1062, 1264, 1883, 2925 [shoulder girdles, spines]
59.   *Murrindalaspis wallacei* Long and Young, 1988

Rhenanida
60.   rhenanid n.g. ANU V1077 [skull and braincase]

Petalichthyida
61.   *Notopetalichthys hillsi* Woodward, 1941
62.   *Wijdeaspis warrooensis* Young, 1978
63.   *Shearsbyaspis oepiki* Young, 1985
64.   *Lunaspis* sp. Young, 1985
65.   petalichthyid n.g. ANU V2859 [skull and braincase]

Ptyctodontida
66.   ptyctodontid n.g. Young, 1976
67.   ?ptyctodontid n. g. ANU V2902 [skull and braincase]

Placodermi *incertae sedis*
68.   placoderm n.g. [reverse neckjoint articulation] ANU V2392 [ADL plate]
69.   placoderm n.g. [indet. bone] ANU V3123 [shoulder girdle plate]

Gnathostomata *incertae sedis*
70.   new genus and species ['fish vertebrae'; Zapaznik and Johnston, 1984]

Incertae Sedis
71.   *Ohioaspis tumulosa* Giffin, 1980